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Nuclear ground-state spin and magnetic moment of ^{21}Mg

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ABSTRACT

We present the results of combined laser spectroscopy and nuclear magnetic resonance studies of ^{21}Mg. The nuclear ground-state spin was measured to be $I = 5/2$ with a magnetic moment of $\mu = -0.983(7)\mu_N$. The isoscalar magnetic moment of the mirror pair (^{21}F, ^{21}Mg) is evaluated and compared to the extreme single-particle prediction and to nuclear shell-model calculations. We determine an isoscalar spin expectation value of $\langle\sigma\rangle = 1.15(2)$, which is significantly greater than the empirical limit of unity given by the Schmidt values of the magnetic moments. Shell-model calculations taking into account isospin non-conserving effects, are in agreement with our experimental results.

1. Introduction

Nuclei far away from β-stability are important test candidates for the nuclear shell model which has proven to be well adapted for the description of nuclear systems near the valley of stability. In this respect, the magnesium isotopes towards both ends of the isotopic chain are of particular interest. The neutron-rich isotopes $^{31-33}$Mg lie in the so-called island of inversion [1–3], a region where particle–hole excitations dominate the ground-state wave functions. At the neutron-deficient side, ^{21}Mg is one of the few accessible $T_z = 3/2$ cases in the *sd* shell [4]. Furthermore, the magnetic moment of the mirror partner ^{21}F is known [5]. This allows the study of mirror symmetry for nuclear systems which have just one unpaired proton or neutron in the *sd* shell. Magnetic moments of $T = 3/2$ mirror pairs have become accessible to investigation through projectile-fragmentation induced spin polarization combined with β-NMR [6] and through laser spectroscopy [7]. From the isoscalar part of the magnetic moment, which is basically the mean of the moments of the mirror nuclei, the spin expectation value can be deduced. In all known cases of $T = 1/2$ and $T = 3/2$ mirror pairs except (^{9}C, ^{9}Li) [8], this value is bounded above by 1 and below by $-j'/(j'+1)$ which corresponds to the Schmidt values for nuclei with $j = l + 1/2$ or $j' = l' - 1/2$ valence orbitals, respectively [9]. The remarkable exception of (^{9}C, ^{9}Li), with a spin expectation value of 1.441(2) [8], has been attributed to admixtures of proton intruder configurations in the ^{9}C ground-state wave function [10]. An anomalous behavior of (^{21}F, ^{21}Mg) has been suggested from the indication of a resonance in an NMR study of ^{21}Mg from projectile fragmentation [11].

A more general model [12] predicts a linear dependence between the g-factors $g = \mu/(I\mu_N)$ of the mirror partners. Independent of theoretical predictions, which deviate considerably from

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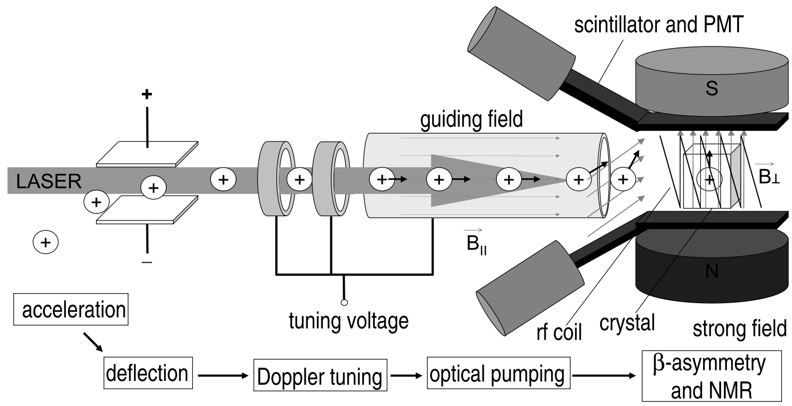

Fig. 1. Schematic of the experimental setup for optical pumping and β-NMR.

the measured moments in some cases, this linear dependence is well reproduced for all mirror nuclei, however with parameters for the slope and intercept deviating somewhat from those calculated with bare-nucleon values.

2. Experiment

In this article we report the measurement of the ^{21}Mg spin and magnetic moment by collinear laser spectroscopy in combination with NMR. At ISOLDE-CERN, a silicon carbide target was exposed to the 1.4 GeV proton beam and the extraction of Mg isotopes was achieved by resonant laser ionization [13] and acceleration to 60 keV. The average production yield of ^{21}Mg was 10^4 ions/s on top of about 10^8 ions/s of ^{21}Na from surface ionization. Only part of this isobaric contamination could be removed by the high-resolution mass separator. For counting β-decay positrons from implanted ^{21}Mg nuclei 3 mm copper degraders were placed between the NMR chamber and the scintillators, stopping most of the lower energy positrons of ^{21}Na. The overall suppression factor for the isobaric contamination was 10^5, making the signals from the ^{21}Mg decay positrons dominant. For g-factor and hyperfine-structure measurements collinear laser spectroscopy and NMR techniques were used in a combined experimental setup shown in Fig. 1. Polarization of the Mg ions in a weak magnetic guiding field was obtained with the use of circularly polarized σ^+ or σ^- laser light tuned to the $3s\,^2S_{1/2} \rightarrow 3p\,^2P_{3/2}$ resonance line at 279.635 nm [14]. In the transfer region to the NMR magnet, the spins follow adiabatically the field direction, changing from longitudinal to transverse, before the electron and nuclear spins decouple in the strong NMR field and the polarized nuclei are implanted into a cubic MgO crystal. For ^{31}Mg the spin relaxation time at room temperature was measured to be 395(63) ms [15]. The value for ^{21}Mg is comparable and therefore longer than the ^{21}Mg β-decay half-life of $T_{1/2} = 121.5$ ms. The positrons emitted in both directions along the field axis were detected by two opposing scintillator pairs coupled to photomultipliers. The β-decay asymmetry a can be defined by the expression $a = [N(0°) - N(180°)]/[N(0°) + N(180°)]$. In order to observe the nuclear polarization produced by the circularly polarized laser light, we measure the β-asymmetry as a function of the Doppler-tuning voltage and obtain the hyperfine structure spectrum. Fig. 2 shows two such spectra for opposite polarization directions σ^+ and σ^-.

The NMR measurements are performed at a fixed Doppler-tuning voltage with the nuclear polarization at a maximum, which in our case corresponds to the right main resonance for σ^- excitation shown in Fig. 2. An rf field is applied to the crystal and the nuclear polarization is resonantly destroyed at the Larmor frequency $\nu_L = gB\mu_N/h$.

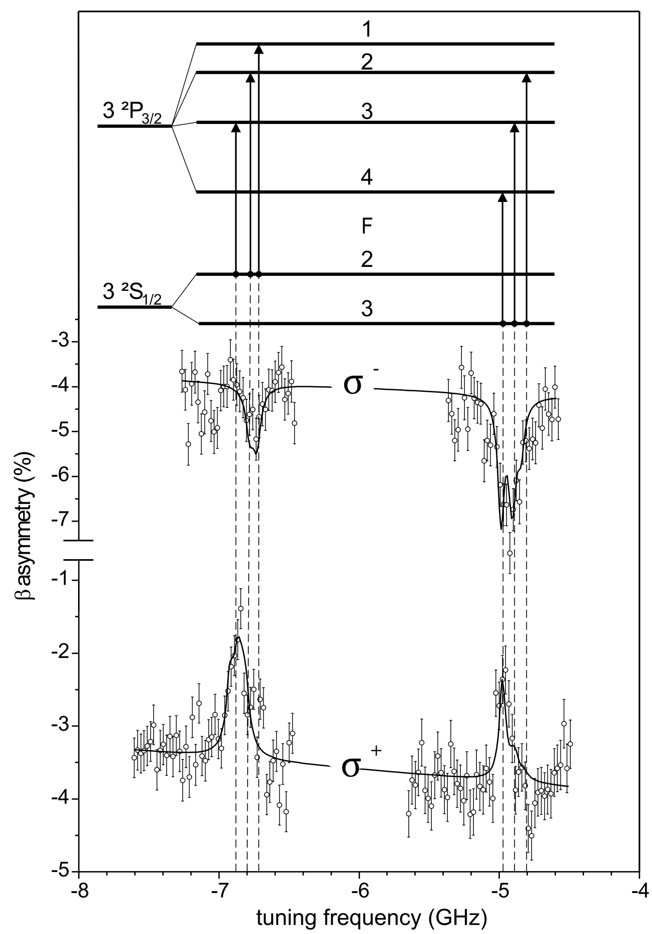

Fig. 2. Hyperfine structure resonances in the β-asymmetry of ^{21}Mg$^+$ for optical pumping with σ^+ and σ^- light and corresponding energy level diagram (not to scale) for a negative magnetic moment. The frequency scale was obtained from the Doppler-tuning and acceleration voltages. The hyperfine structure of the excited state is not fully resolved. The solid lines indicate fits of simulated spectra (see text) to the experimental data.

3. Results

The Larmor resonance obtained with a frequency modulation of 5 kHz is shown in Fig. 3. A fit to this curve has been performed using a modified Lorentz function accounting for the sinusoidal frequency modulation affecting the lineshape. To extract the g-factor of ^{21}Mg from the Larmor frequency $\nu_L(^{21}\text{Mg}) = 860.1(12)$ kHz, the magnetic field strength in the crystal has to be determined

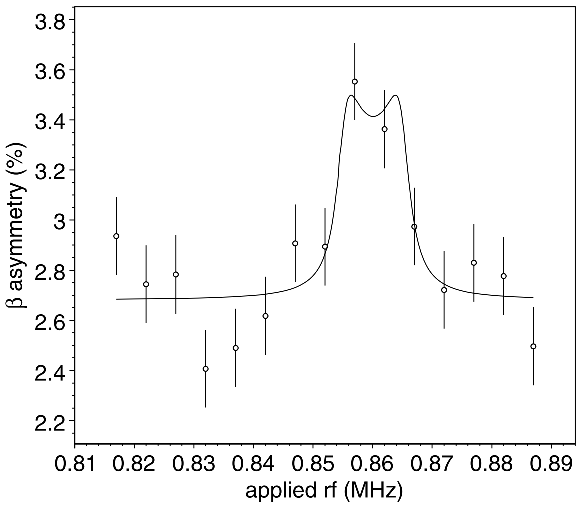

Fig. 3. β-NMR spectrum of ^{21}Mg implanted in MgO with a frequency modulation of 5 kHz.

from a reference measurement, for which we used ^{31}Mg [1] with $\nu_L(^{31}\text{Mg}) = 3866.67(14)$ kHz and $g(^{31}\text{Mg}) = -1.7671(3)$. This results in an absolute value of the g-factor $|g(^{21}\text{Mg})| = 0.393(3)$. The error includes a 0.6% systematic uncertainty due to possible drifts of the magnetic field and a shift in the position of the implantation crystal between the measurement with ^{21}Mg and the reference measurement. The nuclear spin was extracted from an analysis of the hyperfine structure shown in Fig. 2. The hyperfine structure A-factor can be calculated according to $A = [gA_{\text{ref}}I_{\text{ref}}]/\mu_{\text{ref}}$ using the measured g-factor and the A-factor and the magnetic moment of a reference isotope of the same element. For the stable ^{25}Mg we have $A(^{25}\text{Mg}) = 596.254376(54)$ MHz [16], the spin $I = 5/2$ and the magnetic moment $\mu(^{25}\text{Mg}) = -0.85545(8)\mu_N$ [17]. Hence, we obtain $|A(^{21}\text{Mg})| = 684(4)$ MHz. This value was used as a fixed parameter for the fitting routine in which the experimentally observed β-asymmetry is calculated by numerically solving the rate equations for optical pumping and calculating the hyperfine structure pattern [18]. The result of this fit with a nuclear spin $I = 5/2$ is shown by the solid lines in Fig. 2. Other spin values together with the given A-factor as a fixed parameter result in a hyperfine splitting that is either much larger or much smaller than the observed one. Not taken into account is a possible elliptical polarization of the laser beam with small contributions from the opposite σ polarization. This results in modified amplitudes of the individual hyperfine components and may be the reason for the observed deviations from the fitted curves. The sign of the g-factor and hence, of the magnetic moment, can be obtained from the center of gravity of the hyperfine structure compared to the position expected from an approximate calculation of the isotope shift between ^{24}Mg and ^{21}Mg. Depending on the sign of the magnetic moment, the fit of the experimental spectra gives the center of gravity at a distance from the resonance position of ^{24}Mg of either 5.95 GHz for a positive sign or 5.63 GHz for a negative sign, with uncertainties insignificant for the considerations below. Based on a measurement of the isotope shift between ^{24}Mg and ^{26}Mg, $\delta\nu^{21,24} = 3.07$ GHz, this distance can be approximated by the mass-shift contribution (neglecting the small field shift) according to the relation

$$\delta\nu^{21,24} = \delta\nu^{24,26}\frac{m_{24}-m_{21}}{m_{24}m_{21}}\frac{m_{24}m_{26}}{m_{26}-m_{24}}. \tag{1}$$

This results in an isotope shift of 5.65 GHz, with the conclusion that the sign of the magnetic moment is negative, yielding $\mu(^{21}\text{Mg}) = gI\mu_N = -0.983(7)\mu_N$ as a final result.

4. Discussion

According to the nuclear shell model the ground-state configuration of the $N = 9$ isotones, including ^{21}Mg is governed by the unpaired neutron in the $1d_{5/2}$ orbit. We have performed large-scale shell-model calculations with the code ANTOINE [19] using the USD Hamiltonian proposed by Wildenthal [20] to calculate the ground-state configuration and magnetic moment of ^{21}Mg. The calculation predicts ground-state spin and parity of $I^\pi = 5/2^+$ and a magnetic moment of $-0.968\mu_N$ in good agreement with our measurement. According to the calculation the expected configuration with four protons and one neutron in the $d_{5/2}$ orbits contributes only 51.2% to the ground-state wave function. Large contributions are attributed to configurations with the neutron in the $1d_{5/2}$ orbit, two protons in the $1d_{5/2}$ orbit and two protons in the $2s_{1/2}$ orbit (7.6%), or three protons in the $1d_{5/2}$ orbit and one proton in the $1d_{3/2}$ orbit (7.5%). This mixing leads to the absolute value of the magnetic moment of ^{21}Mg being much smaller than the single-particle Schmidt value of $-1.913\mu_N$ [21].

4.1. Isoscalar magnetic moments

The spin and magnetic moment of ^{21}Mg established in this work are important parameters for investigating mirror properties of atomic nuclei, since the magnetic moment of the less exotic ($T = 3/2$) isospin partner ^{21}F is known, namely $|\mu(^{21}\text{F})| = 3.9194(12)\mu_N$ [5]. This allows us to extract the isoscalar spin expectation value $\langle\sigma\rangle$ from the isoscalar magnetic moment [22]

$$\mu_{\text{IS}} = \frac{1}{2}\big[\mu(T_z = +3/2) + \mu(T_z = -3/2)\big] \tag{2}$$

using the relation [23]

$$\langle\sigma\rangle = \frac{2\mu_{\text{IS}}/\mu_N - J}{(\mu_p + \mu_n)/\mu_N - 1/2}, \tag{3}$$

where J is the total angular momentum of the system of nucleons, $\mu_p = 2.793\mu_N$ and $\mu_n = -1.913\mu_N$ are the free-proton and free-neutron magnetic moments. Taking our value for the magnetic moment of ^{21}Mg and the magnetic moment of ^{21}F from reference [5], we get $\langle\sigma\rangle = 1.15(2)$. In the extreme single-particle model, the spin expectation value for nuclei with a $j = l + 1/2$ state is equal to one. Experimental values for $T = 1/2$ nuclei are all found to be smaller than one. For the $T = 3/2$ nuclei, only three mirror pairs with a $j = l + 1/2$ ground state were investigated so far. For (^{13}B, ^{13}O) we have $\langle\sigma\rangle = 0.758(2)$ [31], in agreement with the systematics observed for $T = 1/2$ nuclei. The large value $\langle\sigma\rangle = 1.441(2)$ for the (^{9}Li, ^{9}C) mirror pair was observed for the first time by Matsuta et al. [6] and later confirmed by Huhta et al. [31]. For the third pair (^{23}Ne, ^{23}Al) $\langle\sigma\rangle = 0.82(58)$ (values for the magnetic moments taken from [7,29]), the error is too large to make a final statement. In Fig. 4 the experimental $\langle\sigma\rangle$ values of all known $T = 3/2$ pairs are shown. The moments of the two $j' = l' - 1/2$ mirror pairs are above the lower single-particle limit $-j'/(j'+1)$ in agreement with the systematics known for $T = 1/2$ nuclei. To explain the exceptional cases of $\langle\sigma\rangle > 1$, Mantica et al. [11] introduced isospin non-conserving effects (INC) into the shell-model calculations [32]. One clear isospin symmetry violating effect is the Coulomb interaction between the protons, leading to weaker bound protons compared to neutrons carrying the same quantum numbers. For the (^{9}C, ^{9}Li) mirror pair it has been shown [31] that the shell-model treatment including INC cannot account for the large spin expectation value and still misses 18% of the value found in the experiment. Only the extension of the model space to the sd-shell, allowing for intruder states makes the experimental value reproducible by shell-model calculations.

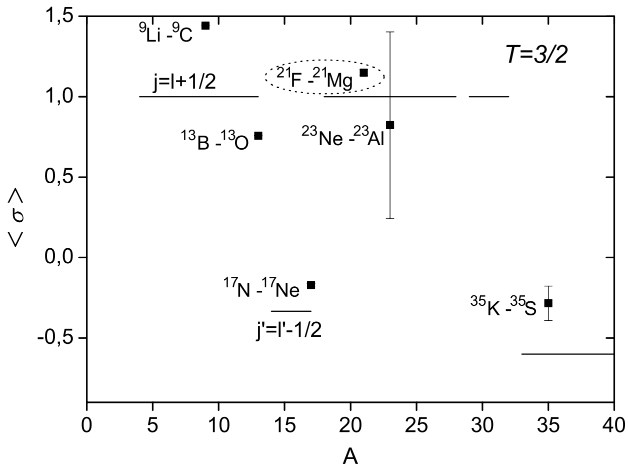

Fig. 4. Spin expectation values for the known $T = 3/2$ mirror pairs shown together with the single-particle limits. The magnetic moments were taken from [5–7,24–30] and for ^{21}Mg from this work.

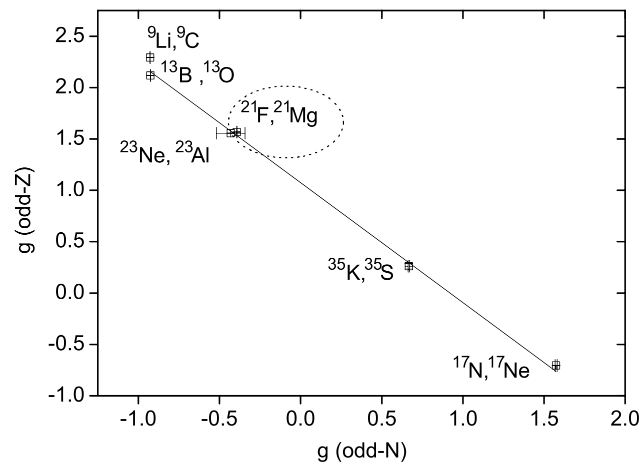

Fig. 5. g-factors of odd-Z versus odd-N mirror nuclei ($T = 3/2$). The solid line shows a linear fit of the data with the parameters $\alpha = -1.167(32)$ for the slope and $\beta = 1.074(30)$ for the intercept. The magnetic moments were taken from [5–7, 24–30] and for ^{21}Mg from this work.

Table 1
Experimental spin expectation value $\langle\sigma\rangle$ for the three $T = 3/2$, $j = l + 1/2$ mirror pairs shown together with theoretical predictions from the single-particle (s.p.) model, the shell model with isospin non-conserving interactions (INC), with the USD interaction [20] for the sd-shell or the PTBME interaction [33] for the p-shell and with the WBP interaction for the p–sd shell [34]

Mirror pair	Exp.	s.p.	INC	USD/PTBME	WBP
(^{21}F, ^{21}Mg)	1.15(2)[a]	1.00	1.15[b]	1.11[a]	–
(^{9}Li, ^{9}C)	1.44(2)[b]	1.00	1.18[b]	1.09[b]	1.47[c]
(^{23}Ne, ^{23}Al)	0.82(58)[d]	1.00	–	0.82[a]	–

[a] This work.
[b] Values taken from [11,31].
[c] Values taken from [10].
[d] Values taken from [7,29].

The isospin-symmetric shell model reproduces rather well the individual magnetic moments of the $A = 21$ mirror partners, giving $-0.968\mu_N$ for ^{21}Mg and $+3.888\mu_N$ for ^{21}F. This corresponds to $\langle\sigma\rangle = 1.11$, which is already greater than unity. With the inclusion of the Coulomb interaction for the protons and asymmetric nucleon–nucleon interactions [32], the spin value changes slightly to $\langle\sigma\rangle = 1.15$ [11], which is in excellent agreement with our experimental value. The experimental results are summarized in Table 1 together with the predictions from the extreme single-particle model and the shell model.

4.2. g-factors

Beyond the systematics of isoscalar magnetic moments, there is an interesting relationship between the g-factors $g = \mu/(J\mu_N)$ that was investigated by Buck and Perez [12] for $T = 1/2$ mirror nuclei. If one assumes that the nuclear moments are produced only by the odd group of nucleons, the g-factors are given by

$$g(\text{odd-}Z) = g_l^{(p)} + \left(g_s^{(p)} - g_l^{(p)}\right)\langle\sigma\rangle/2J \tag{4}$$

for the odd-proton mirror partner and

$$g(\text{odd-}N) = g_l^{(n)} + \left(g_s^{(n)} - g_l^{(n)}\right)\langle\sigma\rangle/2J \tag{5}$$

for the odd-neutron mirror partner, with $g_l^{(p)} = 1$, $g_s^{(p)} = 5.586$, $g_l^{(n)} = 0$, and $g_s^{(n)} = -3.383$ the orbital and spin g-factors of the proton and the neutron. Elimination of the factor $\langle\sigma\rangle/2J$ leads to the linear function

$$g(\text{odd-}Z) = \beta + \alpha g(\text{odd-}N) \tag{6}$$

with $\alpha = \frac{g_s^{(p)} - g_l^{(p)}}{g_s^{(n)} - g_l^{(n)}}$ and $\beta = g_l^{(p)} - \alpha g_l^{(n)}$. A fit to the known data for $T = 1/2$ mirror pairs yielded $\alpha = -1.145(12)$ and $\beta = 1.056(21)$ [12], significantly different from the model values $\alpha_{\text{s.p.}} = -1.199$ and $\beta_{\text{s.p.}} = 1$ which also correspond to the extreme single-particle limit. It has been shown recently [35] that this deviation is not only caused by the contribution of the even group of nucleons being neglected. In fact, a correction for this effect only moves the points representing pairs of g-factors along the line defined by Eq. (6). Shell-model calculations do well in describing the contribution from the even nucleons, but the main effect is supposed to be caused by meson-exchange currents [35]. Fig. 5 shows a plot of the g-factors for all $T = 3/2$ mirror pairs presently known. A linear fit to these data gives $\alpha_{(T=3/2)} = -1.167(32)$ and $\beta_{(T=3/2)} = 1.074(30)$. As shown for the previously known cases [36], these values are in agreement with the fitting parameters for $T = 1/2$ nuclei, and including the ratio of the (^{21}F, ^{21}Mg) mirror pair does not change the parameters significantly.

5. Conclusion

With a combined laser spectroscopy and β-NMR experiment we measured the nuclear spin and the magnetic moment of the neutron-deficient isotope ^{21}Mg. The combination with known data of the mirror nucleus ^{21}F allowed us to extract the isoscalar part of the magnetic moment and hence, the spin expectation value, which is significantly greater than one. In contrast to the other $T = 3/2$ mirror pair (^{9}Li, ^{9}C), that also shows an enhanced spin expectation value, the (^{21}F, ^{21}Mg) case can be well reproduced by shell-model calculations if isospin non-conserving interactions are taken into account. The investigation of the g-factors shows that our values are in agreement with the known systematics of mirror nuclei.

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